Report on Program Supported by
NASA Grant NGR-05-007-066

Interaction Between Ion Beams and Plasmas

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December 1, 1966

Progress Report N-2

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I. INTRODUCTION

In this paper we wish to report the preliminary results of the interaction between a low energy cesium ion beam (1 to 30 ev) and a thermal cesium plasma (.25ev). A schematic of the system used is shown in Fig. 1.

The cesium plasma is produced by contact ionization on a hot tungsten plate in one end of a Q machine.[1] The cesium ion beam is produced by a gun which is essentially the same as the one developed by Sellen et al.[2] The ions are formed on the surface of a porous tungsten plug which is fed by a beam of C_s atoms from an oven behind the plug. The C_s ions are then accelerated by the accelerating grid and then decelerated to the plasma potential. The beam velocity can be varied from 1 to 15 times the plasma ion thermal velocity (a_i). The beam and plasma width is approximately 2.5cm. The maximum beam density was 5×10^9/cc. The plasma density ranged from 5×10^9/cc to 10^{11}/cc.

The experimental work can be broken down into two main catagories. The first catagory is the investigation of stability limits for low frequency oscillations in an ion beam-plasma system confined by a magnetic field. The ion beam is directed along the magnetic field. The density gradients supported by the magnetic field give rise to an aximuthal component to the unstable wave, thus changing the wave character from that in a homogeneous infinite plasma.

The second catagory is the investigation of the attenuation and the phase velocity of low frequency "ion acoustic" waves in a stable ion beam-plasma system. The waves are excited and received by grids immersed in the beam-plasma system.

II. Density Profiles

The cross-section density profiles of the beam and the plasma were measured separately in order to ascertain that the beam was centered in the plasma. The position of the plasma in the chamber can be adjusted to remedy any misalignment. The density profiles after the final adjustment are shown in Fig. 2.

III. Stability Limits of an Ion Beam-Plasma System Confined by a Magnetic Field

One of the initial goals of this experiment was to verify the theoretical work by Fried and Wong[3] which predicted the stability limits for electrostatic "ion acoustic" waves propagating parallel to a Maxwellian ion beam which is injected through an infinite homogeneous Maxwellian plasma with no magnetic field. However the presence of the magnetic field and the resulting density gradients give rise to additional terms in the dispersion relation[4] which can change the stability limits of the system. These additional terms also result in a component of the wave which is perpendicular to the magnetic field, thus giving a helical wave of the type described by Kadomtsev.[5] In the limit of zero density gradients the helical waves go over into ordinary ion acoustic waves. The presence of this type of wave is borne out by two experimental observations.

1. A spontaneous oscillation was observed which had stability limits close to those predicted by Fried and Wong. (See Fig. 3). At a beam to plasma density ratio of .27 and a beam velocity of 2.6 a_i (a_i is the plasma ion thermal velocity), there were no oscillations in the plasma. As the beam velocity was increased an oscillation appeared with a frequency of $\simeq$ 20 Kc. The amplitude of the oscillation increased with increasing beam velocity until a beam velocity of $4.a_i$ was reached. Further increase in beam velocity resulted in a decrease of the oscillation amplitude. At a beam velocity of $5.2a_i$ the oscillation amplitude had returned to zero. The fact that the oscillation had a maximum amplitude at beam velocities slightly greater than the phase velocity of an ion acoustic wave indicates that the instability is caused by a resonance of the beam particles with the ion acoustic wave. As the beam velocity is increased the particles go out of resonance with the wave and the oscillation disappears.

The oscillation was detected by a planar grid situated perpendicular to the magnetic field and beam direction. Measurements with a small probe showed that the oscillation amplitude was maximum in the center of the plasma column. This indicates a wave propagating along the magnetic field. Also, on the edge of the plasma, where there were large density gradients, phase measurements showed that the oscillation had an azimuthal component. This indicates a helical type wave or two uncoupled waves-- an axial wave in the center of the plasma and an azimuthal wave on the edge.

2. Phase measurement of a similar oscillation under slightly different conditions gave another indication of the presence of a azimuthal wave. The phase change of the oscillation was measured between two probes situated in a common axial plane but with a 90° azimuthal angle between them (see Fig. 4). As the beam velocity is increased from $2.6a_i$ to $8.a_i$, the phase difference between the two probes changes smoothly. This indicates that the phase velocity or the wave number of the azimuthal component is dependent on beam velocity.

The two phenomena discussed above were observed on the last day of operation and will be investigated thoroughly in subsequent runs.

IV. Damping of Low Frequency Longitudinal Waves

In order to study the attenuation of ion waves in an ion beam-plasma system, low frequency electrostatic waves were excited on a large plane grid and received on a similar movable large plane grid in a manner similar to Wong, D'Angelo and Motley.[6]

Attenuation and phase velocity measurements were made for various values of beam velocity and beam to plasma density ratio. The attenuation rate is less than for ion acoustic waves in a plasma with no beam. (See Fig. 5). For low beam velocity ($V_{beam} < 8a_i$) the attenuation rate varies inversely with the ratio of beam density to plasma density. When plotted in terms of the dimensionless parameter $Z = \frac{wx}{a_i}$ the attenuation rate is independent of frequency. (See Fig. 5). For high beam velocities ($V_{beam} > 12a_i$) the waves were essentially undamped. The explanation of this may be as follows. There is an instantaneous conduction signal between the exciting grid and the receiving grid. In order to measure the amplitude of the propagated wave the time between the end of the excitation and the end of the received propagations must be greater than the time of a half cycle. Since the phase velocity of these waves is high the two grids must be far apart to see a half cycle difference between the two signals. At these distances we would expect to see the "electron contribution" to the ion acoustic wave. This wave is very slowly damped.

The phase velocity of the wave depends strongly on the beam velocity. The dependence on density is small. The phase velocity is always less than the beam velocity and increases with increasing beam velocity. The difference between phase velocity and beam velocity also increases with increasing beam velocity. If the wave was an ion acoustic wave traveling backwards in the beam, the phase velocity in the lab frame would be less than the beam velocity, as observed, but the difference between the two would remain constant. This is contrary to observation. The observed dependence of phase velocity on beam velocity indicates the wave is traveling in the combined beam plasma system.

V. Microwave Detection System

A microwave detection system was used in place of the receiving grid to measure the amplitude of the waves. The results were essentially the same as the grid detection system. One difficulty encountered in using the microwave system was that a single measurement took so long that the plasma parameters would change over the course of a series of measurements, thus limiting the usefulness of the microwave system. The microwave system was also used in an attempt to detect the response of the beam-plasma to oscillations excited at amplitudes approximating those of thermal fluctuations. No conclusive results were obtained.

VI. Noise Spectrum of Beam-Plasma System

Observations were made of the frequency spectrum of the plasma with and without the beam, and for several beam velocities. The range of frequencies examined was from 0 to 4 MHz. The presence of the beam made no noticeable difference in noise spectrum in this range.

VII. Computer Program

A computer program is being written to calculate the spatial behavior of the amplitude and the phase of the wave potential. A method similar to that described by Gould[4] is being used. Difficulties have been encountered in the numerical integration of the inverse Fourier transform due to the fact that the dispersion relation varies rapidly with wave number. Present results give phase velocities which agree approximately with experiment. However the computer results for amplitude variation is considerably different from that obtained by experiment. This may be due to a number of reasons.

1. Magnetic field and density gradient effects.
2. Boundary effects at grid and at ends of plasma columns.
3. Collisional effects (not accounted for in theory).

VIII. Future Work

Further experimental work is necessary to determine the characteristics of the unstable wave. Phase measurements will be made to determine if the wave is helical or is two separate waves, one in the center of the plasma and one on the edge. Stability limits will be determined and the amplitude and frequency dependence on the various system parameters will be measured. Concurrently with this experimental work, a theoretical analysis of the complete dispersion relation will continue, including density gradient and magnetic field effects. Solutions will be obtained in the asymptotic limits of the various system parameters. Subsequent to the results obtained in the asymptotic limits a numerical solution of the exact dispersion relation will be obtained either on the UCLA on-line computer facility or by a Fortran program written for the UCLA IBM 7094.

Other experimental work considered for the future:

1. Effect of an ion beam on the damping of azimuthal drift waves in a plasma with density gradients in a magnetic field.

2. Investigation of the effect of an ion beam on the noise spectrum of a plasma. We will extend the observed spectrum into the 10 Megahertz range.

3. Investigation of the electron-ion wave predicted by Ohnuma and Hatta[8] for high velocity ion beams.

4. Continued investigation of attenuation of ion acoustic waves in a stable beam-plasma system.

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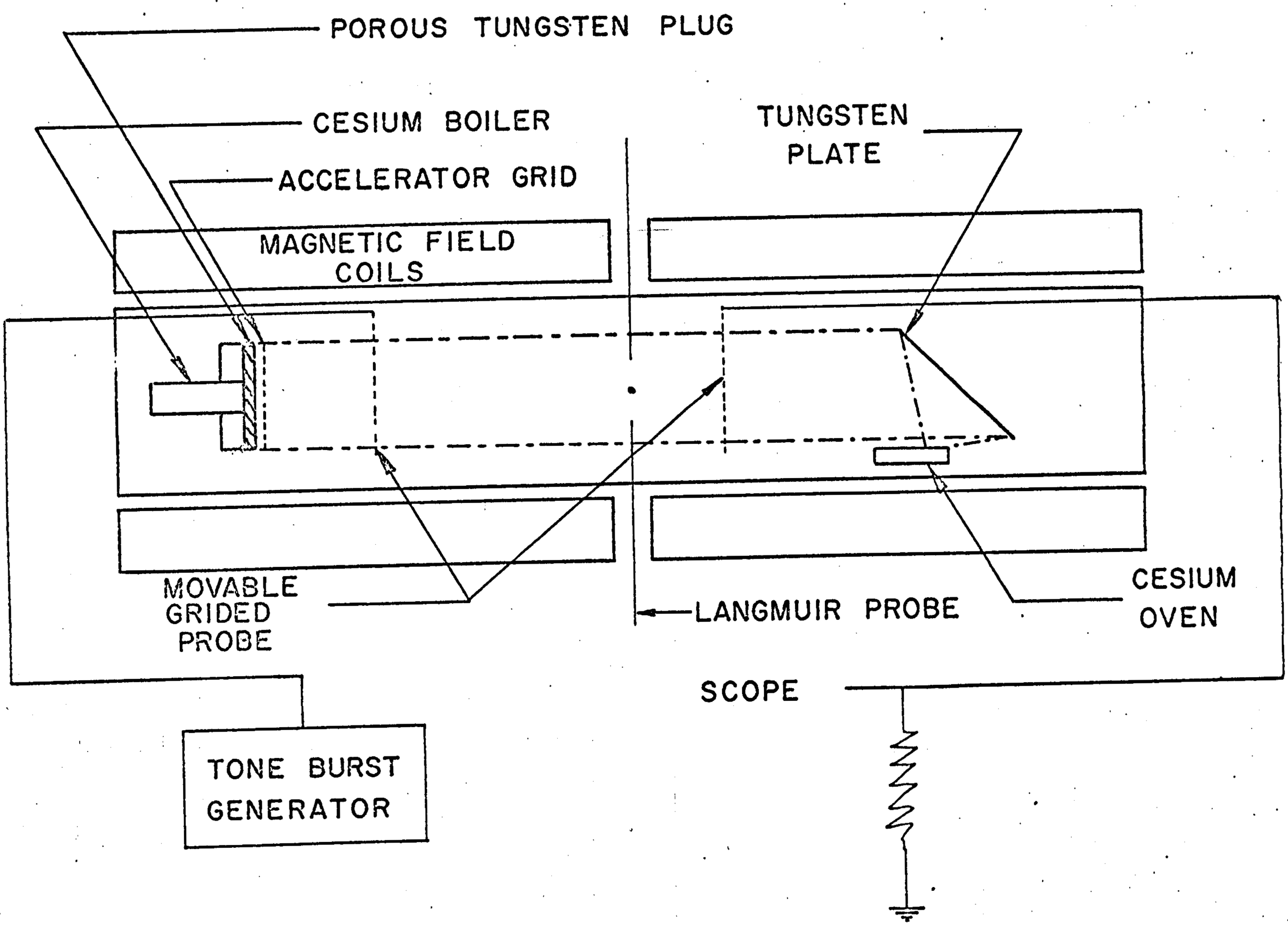

Figure 1 SCHEMATIC DIAGRAM OF APPARATUS

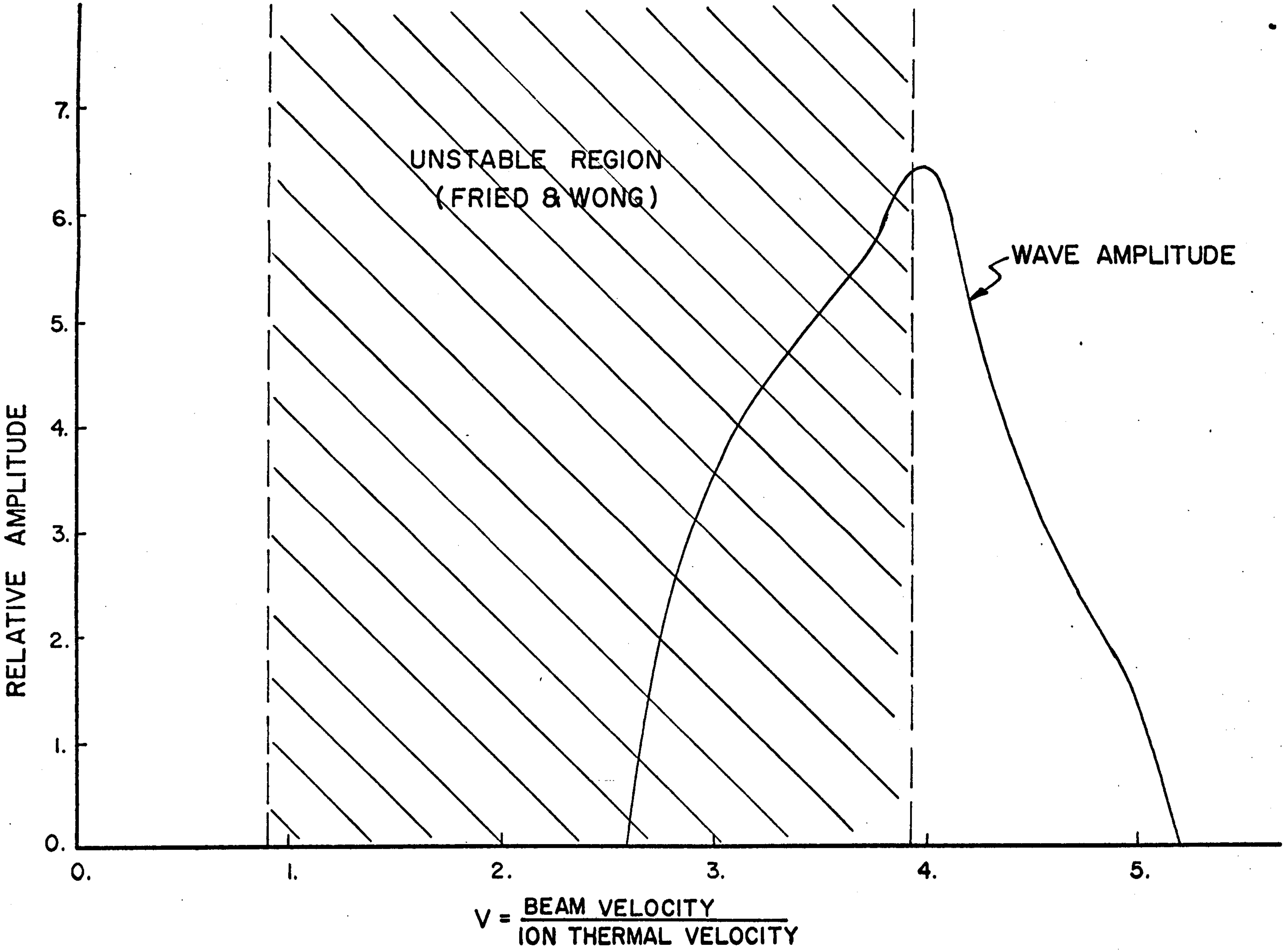

Fig. 3 - Amplitude of Unstable Oscillation vs Beam Velocity

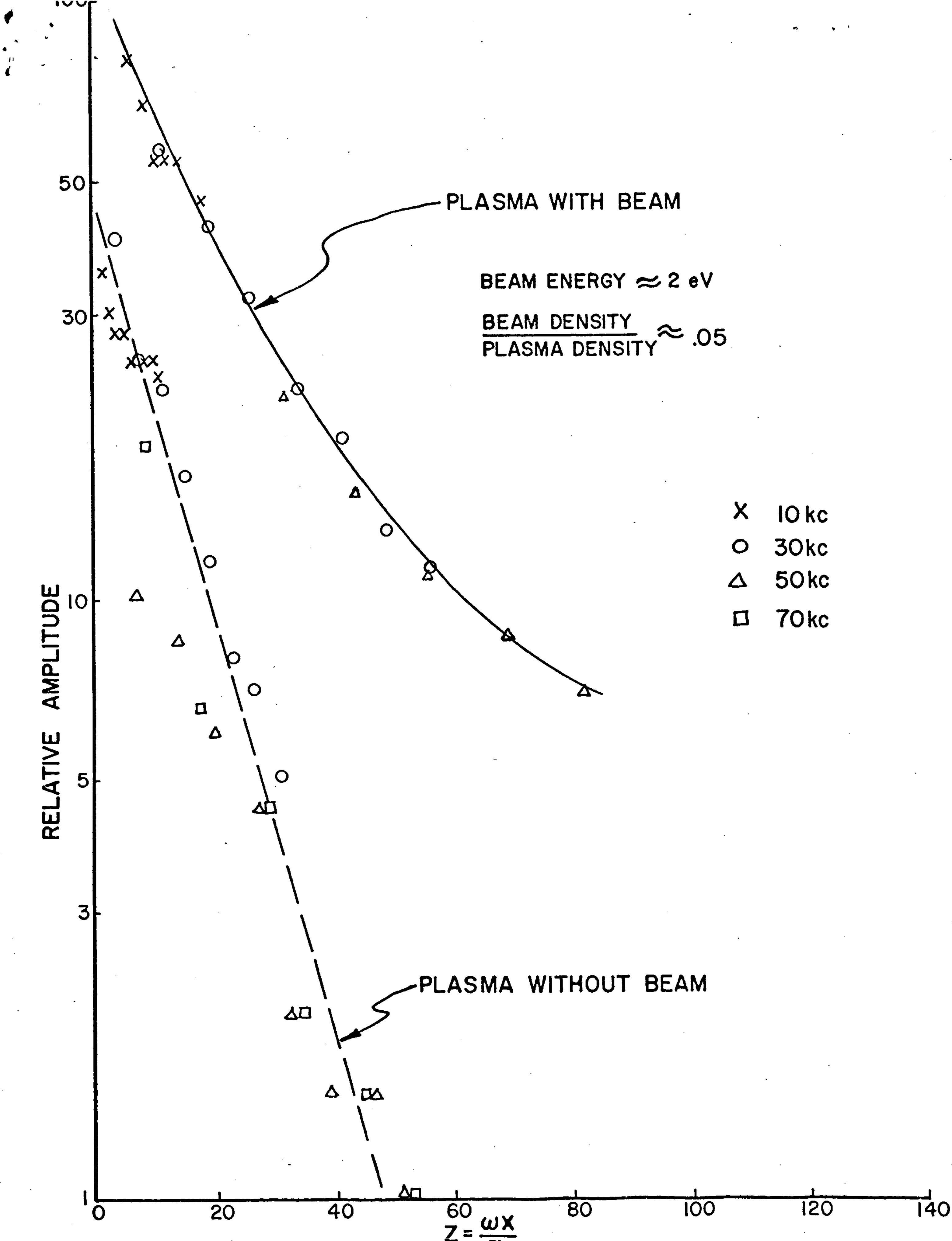

Fig. 5,- Damping of Longitudinal Wave vs. Longitudinal Distance